TENSILE AND COMPRESSIVE BEHAVIOUR OF EARLY AGE CONCRETE

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ABSTRACT

This paper presents a series of experimental tensile results that have been conducted on concrete at early age, typically less than 3 days. The test method and procedure for measuring uniaxial tensile strength using concrete cylinders are reported. The tensile strain capacity of concrete under uniaxial tension using the adopted direct tension test method is presented. The test method adopted seeks to overcome the difficulties of centralizing and aligning the test specimen, and eliminates direct point loading from either steel reinforcement [1] or using square sections [2], which can influence the post ultimate strain softening.

This paper presents the relationship between direct and indirect tensile strengths and compressive strength of typical precast concrete panel mix and shows their correlations. The significance of understanding the behaviour of concrete in tension is detailed and the role of tensile properties with fracture mechanisms is explored. It is shown that the relationship between tensile strength is not dependent on compressive strength and more reliant on mix composition and concrete age. It is also demonstrated that indirect and direct tensile tests will reflect different tensile strengths. The conclusion summarises that the tensile strength, less than 3 days old, measured by the test method employed and highlights the differences against tensile split tests, and compression cylinders.

Keywords: Tensile concrete strength, uniaxial direct tensile test, tensile material properties of early age concrete

1 Introduction and background

Concrete is relatively weak in tension, but this should not mean the tensile capacity should be ignored, it still has an important role to play when considering early age concrete properties, especially when you are considering lifting precast elements at an early concrete strength typically within 24 hours. The more efficient and sophisticated design techniques become, the better the understanding of material properties needs to be, and in the case of tensile properties the interest is in relation to the cracking behaviour of early age concrete caused by lifting inserts.
Concrete passes through different states from the initial mixing to a stable state several months later. During the early stages of concrete strength development, that lifting inserts depend on, is related to a function of various failure modes, refer figure 1, and is primarily a function of micro-crack propagation.

The test method used in this paper is similar to the less commonly applied direct concrete tension method. This test was not established to redefine a new test regime, but to research the relevance of this test method in relation to lifting inserts used in prefabricated concrete elements. This method has overcome the difficulties of centralizing and aligning the specimen, which is inherent in other test methods. It is assumed that this test method minimizes compressive stresses in the test specimen whilst the load is being applied. Two concrete strengths were used, which represent typical mixes used in the precast industry. These were selected to study the relationship between compressive strength and direct tensile strength.

2 Tensile Properties of early age concrete and measurement

2.1 Why use direct tension tests?

Correlations have previously been obtained between flexural tensile strain capacity and flexural strength for various concrete ages (Welch [2], Olanapo [3]). Approximate short term strain capacity in flexure can be estimated if the modulus of elasticity and strength are known. It has been shown (Brooks [4]) that the thermal strain capacity of concretes of similar strength and workability is related to the type of coarse aggregate used, and there is a good correlation between strain capacity and strength/modulus of elasticity for these results. As far as tensile strength is concerned the splitting tensile test (Carnerio and Barcellos [5]) and the three (or four) point bending test (Hillerborg [6]) have been widely applied. There are some consistent results obtained between flexural tensile strain capacities. But all these tensile tests have the disadvantage of a non-uniform state of stress, which is superimposed over the local stress fluctuations that are caused in concrete. With the splitting test a very steep stress gradient develops, and just below where the load is applied compressive stresses develop perpendicular to the axis of the load. This combination of local stress gradients interacting may result in a variance of crack development dependent on aggregate position, size and volume. Thus it may be suggested that various configurations of calibration of the splitting test machine may be necessary versus concrete mix and type being tested.

Whereas the bending test has its own set of issues to consider, like self-weight of the specimen which may alter the post failure (softening) effect of the test result. Again the damage around the applied load may alter the stress gradients, and crack propagation, for different material types. This results in a degree of confinement within the Fracture Process Zone.

Factors affecting the relationship between tensile stress and strain show that this is not a constant value (Welch [2]) and is relative to the test method, the type and size of aggregate, the gauge length, the water/cement ratio, curing conditions, age of concrete and test loading rate.

2.2 The derivation of tensile strength

The tensile strength and tensile strain capacity of concrete are used widely in the assessment of crack occurrence in concrete members. Based on the tensile strain capacity rather than the tensile strength, it is more convenient and simpler to evaluate cracking where the forces can be expressed in terms of linear changes. The tensile strain capacity can be evaluated from the Modulus of Rupture test, where ACI224 Cracking of concrete members in direct tension [7] suggests the following expressions to estimate tensile strength as a function of compressive strength

Modulus of rupture: $f_r = g_r . \sqrt{w_c . f'_{cm}}$ (1)

Direct tensile strength: $f_r = g_t . \sqrt{w_c . f'_{cm}}$ (2)

where:
w_c= unit weight of concrete (kg/m3)
f'_{cm} = compressive strength of concrete at time of test (MPa)
g_r= 0.012 to 0.021 (0.013 – 0.014 is recommended)
g_t = 0.0069

Hunt [8] measured tensile strain capacity from fully restrained concrete prisms in which temperature differentials were induced to bring on the onset of shrinkage cracks. Houghton [9] proposed that the estimated tensile strain capacity is evaluated from the modulus of rupture divided by the modulus of elasticity. Liu [10] developed an approximation method for tensile strain capacity of concrete using compressive strength and the modulus of elasticity. It can be seen that the elastic modulus of concrete increases with age, as noted by ASTM C469-10 [11].

Age	18hrs	1day	2days	3days	7days	28days
NSC	12.95	14.92	16.12	15.96	24.04	25.47
HSC	10.53	18.88	22.39	28.24	30.02	33.05

Table: E Modulus of concrete

Whereas Wee [12] presented the variation of tensile properties of concrete under various degrees of stress. In BS8110 Structural use of concrete [13] the tensile strain capacity of concrete using granite as a course aggregate was used.

2.3 Factors affecting tensile strain capacity

Although it is convenient to assume a constant tensile strain capacity; mix composition, curing conditions, specimen size, gauge length, loading rate and the presence of a notch, affect the capacity in different proportions. The tensile stress-strain curve of concrete, figure 1, shows the curve, up to 75%, as almost linear, thereafter the pre-peak nonlinearity due to micro-cracking occurs. The softening response corresponds approximately in two parts, the first a descending one in which strain localization occurs and the second the later descending part with a long tail (Nomura [14]).

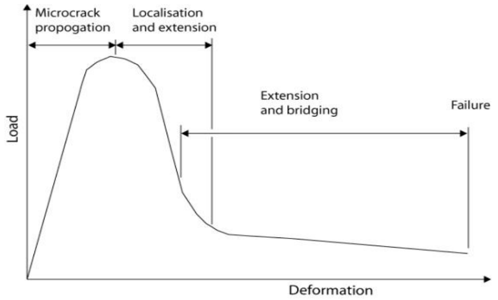

Figure 1 - Simple schematic showing a load deformation curve of concrete in tension (Nomura [14])

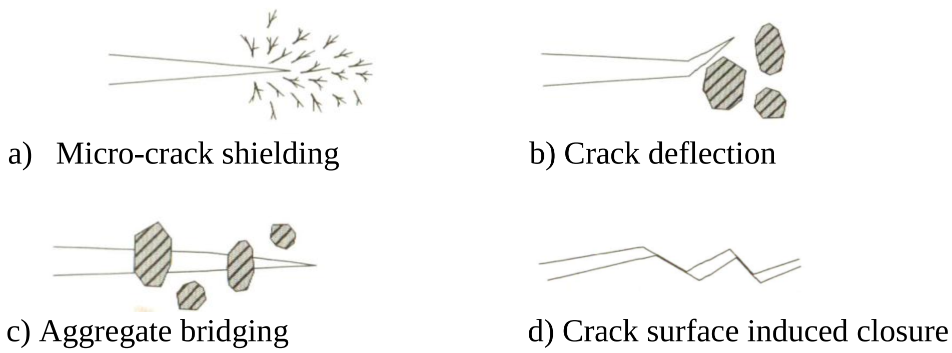

Figure 2: Crack propagation interactions of concrete in tension

The large area spread by microcracks in concrete is termed microcrack shielding, figure 2a. The reasons for shielding are that during fracture, the high stress state near the crack tip causes the preexisting flaws, which result from water filled pores, air voids, shrinkage and thermal shock due to the hydration process. Crack deflection, figure 2b, occurs when the path of least resistance is the path around the course aggregate, and during early concrete age this maybe the predominant crack path, i.e. the applied loads are not sufficient to fracture the course aggregate. Bridging, figure 2c, occurs when a crack has advanced beyond an aggregate that continues to transmit stresses across the crack until it ruptures or is pulled out. During grain pull-out, figure 2d, or the opening of a tortuous path, there is some mechanical interlock between the faces. This causes energy dissipation through friction and localized compression, and some bridging across the crack. It is suggested that tensile strength is directly related to microcrack propagation, and at early age the tensile capacity is gained from paste crack resistance, adhesion and mechanical interlock to course aggregate.

3 Experiment apparatus and procedures

The test specimen, figure 3, was developed to ensure a fracture would occur in the narrowest section of the cylinder throughout all concrete tensile strengths.

Figure3: Direct tension test specimen

3.1 Test Procedure

CONCRETE MIX: The cementitious materials used was GP Portland cement, as per AS3972 General purpose and blended cements [15], and aggregate and sand as per AS2758.1 Aggregates and rock for engineering purposes [16]. The concrete batch was specified with a typical w/c ratio of 0.4.

CYLINDERS: Cylinders used for testing were standard 100mm diameter by 200mm long, figure 4, a cylinder throat was inserted into the mould to create the reduced section. Concrete was prepared in plastic cylinder moulds in accordance with AS1012.8.1 Methods of testing concrete [17], with dimensions of 100mm diameter x 200mm long capped cylinders. The cylinder throats effectively reduced the cylinder diameter by 40mm, with a 30mm long reduced section, figure 4, where the plastic throat was stripped after demoulding. The cylinders were de-moulded at time of test and all naturally cured in a stable shaded atmosphere with a temperature range of 10 to 25^{o}C. 30 cylinders were prepared from a single concrete batch, and tested at 1, 2, 3, 7 & 21 days. At each of the 5 time intervals there were 3 cylinders tested in compression, 3 cylinders tested in direct tension and 1 cylinder in indirect tension. The total time to test the 7 cylinders was within 4 hours. After de-moulding, the ends of the cylinder were prepared in accordance with AS1012.8.1 [17].

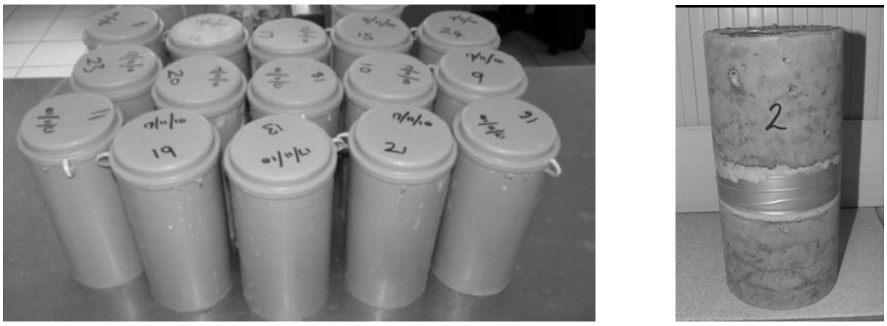

Figure 4: Cylinder moulds, and a demoulded cylinder prior to reduced section being stripped

COMPRESSION TEST: The compression cylinders were tested in the methodology as stated in AS1012.8.1 [17]. Compression testing was conducted by fitting the cylinders with rubber caps at each end, see below picture. Compressive stress was applied at 20MPa/min until the peak load was achieved and compressive rupture of the cylinders occurred.

Figure 5: Compression test setup, and a typical failure at early age (1 day)

TENSILE TEST: Tensile testing was conducted by capping each end of the cylinders with precision steel caps bonded with epoxy adhesive. The cylinders were then fitted between the universal joints of a tensile testing machine, refer below picture, and loaded at 1.0mm/min until tensile rupture of concrete occurred. Test load and tensile displacement data was recorded for each test.

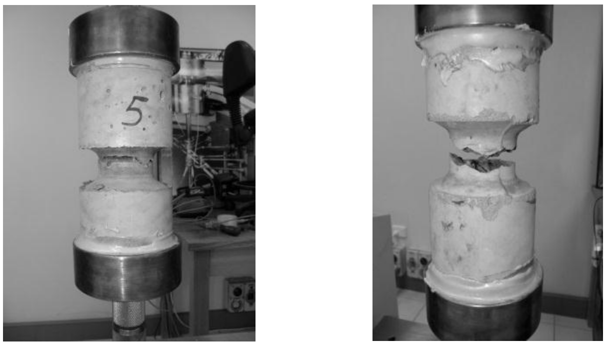

Figure 6: Tensile test setup, and typical failures of tensile cylinder

SPLIT CYLINDER TEST: The cylinders were tested in the methodology as stated in AS1012.10:2000 [19] for indirect tension measurement. Indirect tension, or Split testing was conducted by fitting the cylinders horizontally inside 2 plates lined with hard board, figure 7. Compressive stress was applied at 20MPa/min until the peak load was achieved and rupture of the cylinders occurred.

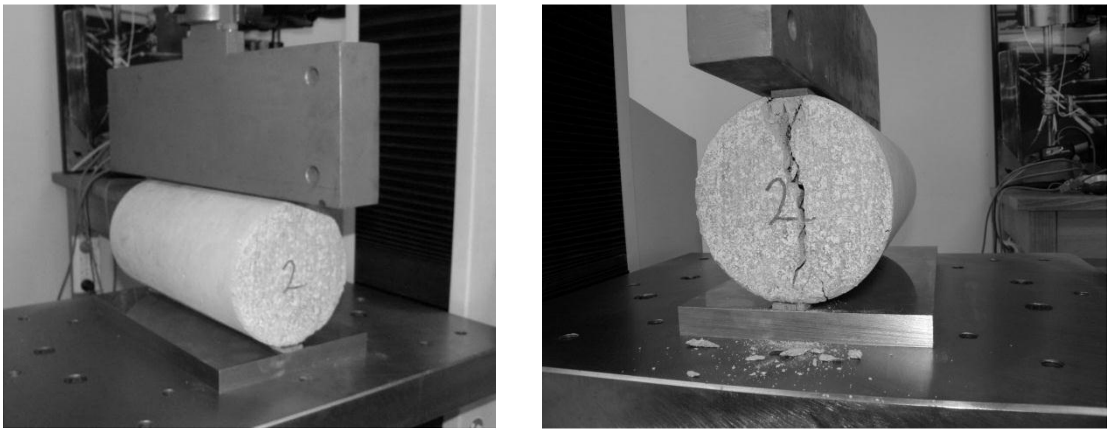

Figure 7: Split test setup, and typical fracture.

4 Test Results

Typical stress-strain curves recorded from the direct tension tests adopted are shown in Figure 4. As noted by Wee, [12], since concrete is a non-homogeneous material, the curves should deviate at higher stress levels. This deviation is dependent on the stress concentrations at the tips of the microcracks, or crack pattern, existing in the test specimen. The load was applied at 1mm/min for each tensile specimen.

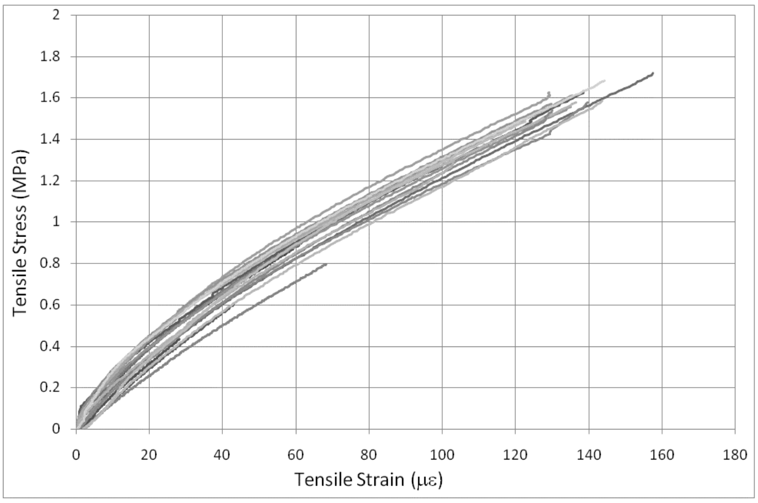

Figure 8 - Stress-strain curves of concrete in direct uniaxial tension

The figures 9 to 14 show the relationship between the compressive and tensile strengths against age. As expected, concrete with lower w/c ratios gain strength faster, figure 8 and

9. Additionally Mindess [19], recorded for the same w/c ratios, the use of larger aggregate reduces the specific area of the aggregate and hence a lower bond strength, resulting in a reduction of concrete tensile strength.

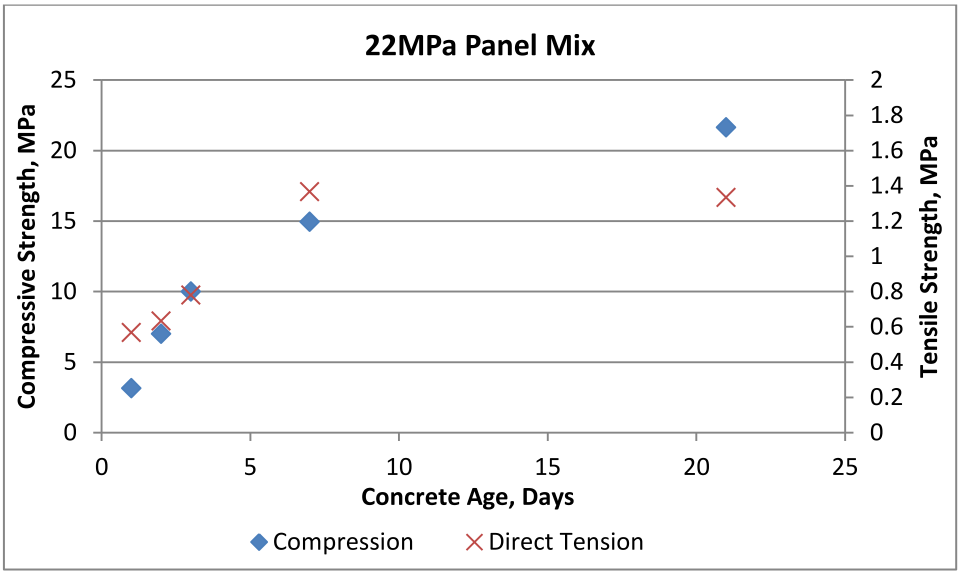

Figure 9: Concrete strengths observed for 22MPa batch

Figure 9 shows the compressive and tensile strength observed, and also showing that the tensile strength stabilized after day 7 whilst showing a typical compressive strength gain curve. Both compression and tensile cylinders were made from the same concrete batch and cured under the same conditions.

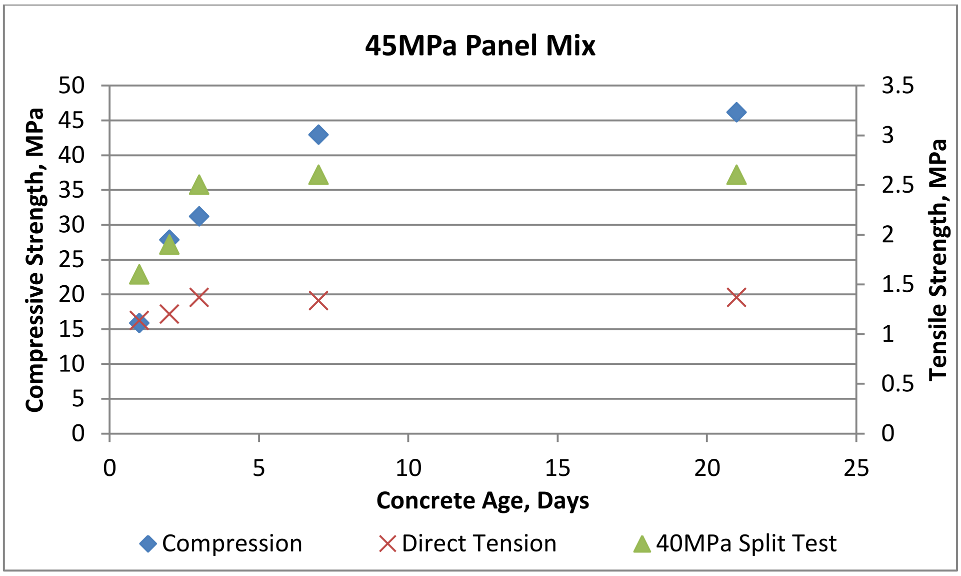

Figure 10: Concrete strengths observed for 45MPa batch

Figure 10 shows the compressive and tensile strength observed, and also showing that the tensile strength stabilized after day 7 whilst showing a typical compressive strength gain curve. Both compression and tensile cylinders were made from the same concrete batch and under the same conditions.

Less than 3 day old concrete developed tensile strengths at different rates than the when measured by direct or indirect methods. A maximum tensile strength of just over 2.5MPa was measured by the indirect method, whereas a maximum tensile strength of 1.4MPA was measured by the direct method.

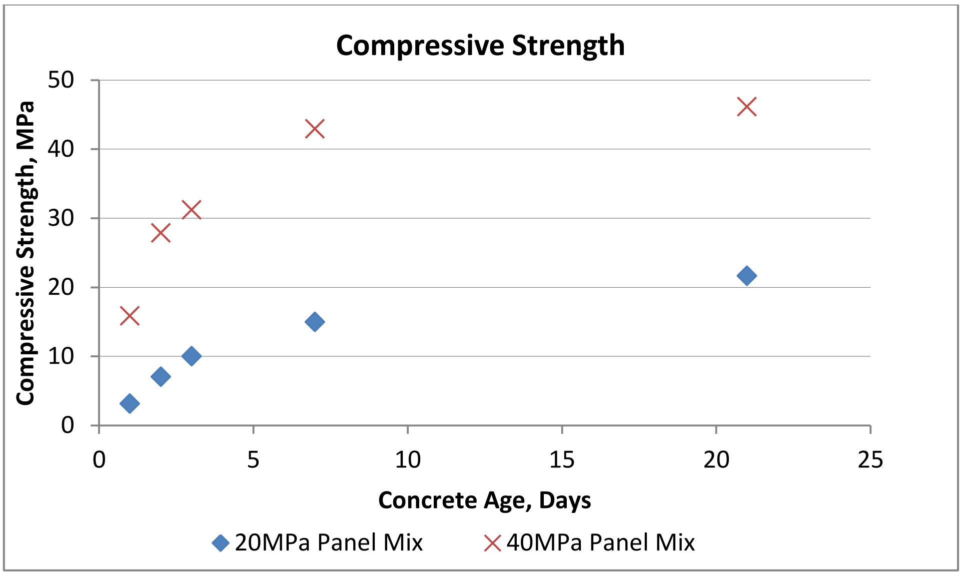

Figure 11: Concrete compressive strengths measured for each batch

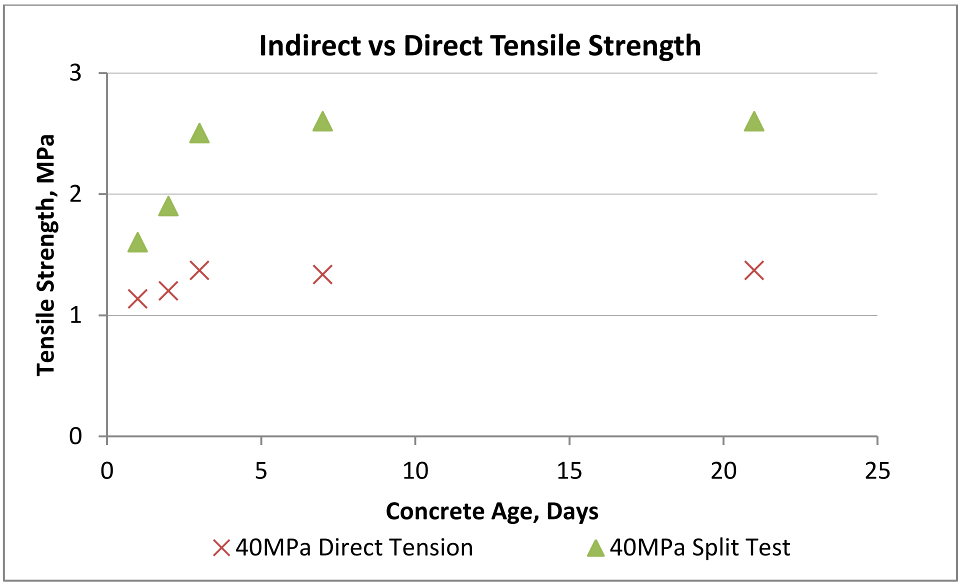

Figure 12: Comparison of measured indirect and direct tensile strengths

Comparing the indirect and direct tensile strengths shows a gain of 1MPa over 3 days (indirect) and a gain of 0.3MPa (direct)

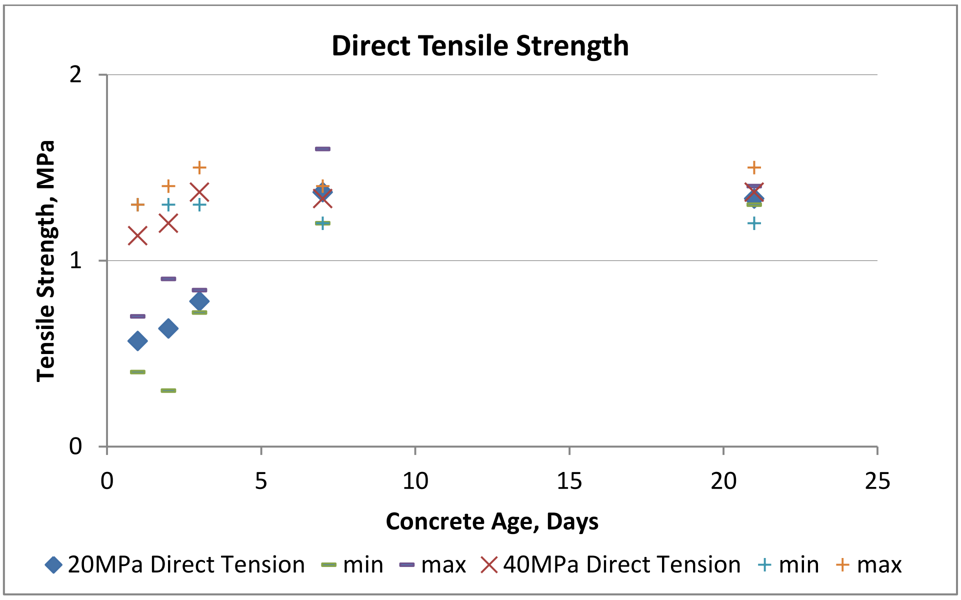

Figure 13: Comparison of measured direct tensile strengths for both batches

When comparing the measured direct tensile strengths, including minimum and maximum values, it is noted a difference of over 0.6MPa during the first 3 days.

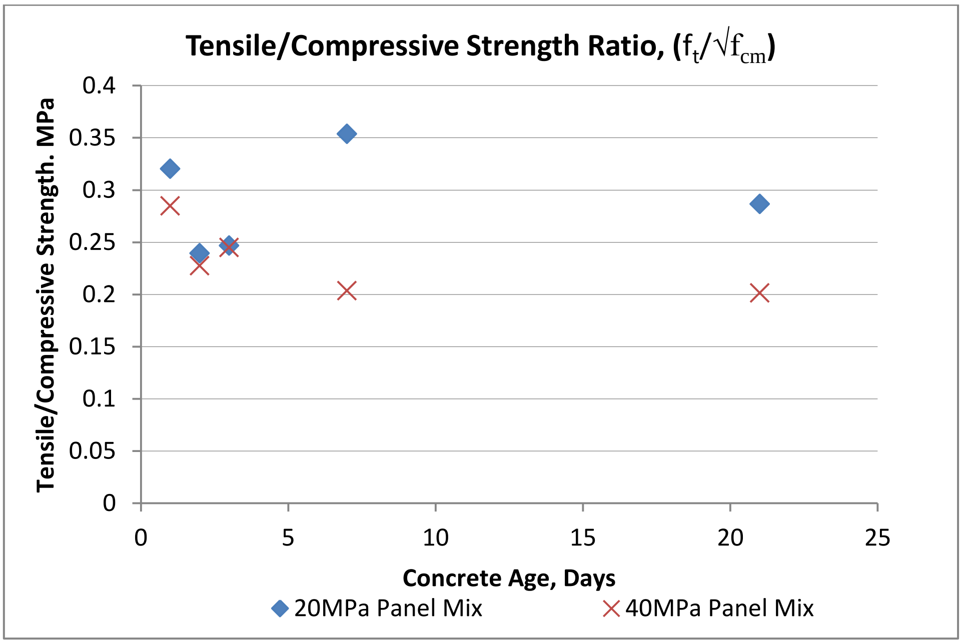

Figure 14: Comparison of tensile/compressive ratios between both batches

Figures 8 and 9 display the relationship between tensile to compressive strength ratio and age of concrete for both concrete batches. The tensile to compressive strength ratio, figure 13, decreases as concrete matures to day 2 and then increases to day 7. This shows the rate of strength rate in tensile strength is smaller than the increase in compressive strength.

The relationship between tensile to compressive strength ratio and compressive strength of the 2 types of concrete compressive design strength are depicted in figure 13.
The tensile to compressive strength ratio decreases as compressive strength increases, or concrete ages. By implication the tensile strength gain is smaller than the increase in compressive strength. For these tests the tensile to compressive strength ratio varies from 0.2 and 0.35, whereas the data from Mindess [19], ranged from 0.1 to 0.06 using the indirect test method.

For concretes that yield lower tensile strength the smaller value of tensile to compressive strength ratios, these finding are supported by Wee et.al. [12].

5 Conclusion

Based on the mix proportions, cementitious materials used and the experimental method adopted in this test analysis, the following conclusions can be made:

1 The tension test procedure, which is designed for ease of use, and is required to have a low coefficient of variation and accuracy of concrete tensile reading to be meaningful, produces a larger distribution of results than other direct methods of testing

2 For different design strength concrete mixes, the tensile strength gain rate varies, and measures lower tensile values than the split test.

3 Further experimentation to establish tensile strength gain in relation to the onset of hydration is necessary to further the tensile properties of precast concrete to assist the designer of lifting inserts.

4 Tensile strength of concrete increases with curing age at a lower rate than compressive strength. The direct tensile to compressive strength ratio varies between $0.2\sqrt{f'_c}$ and $0.3\sqrt{f'_c}$

This uniaxial tension test has not been fully explored to produce a reliable and consistent indication of concrete fracture mechanisms. The uniaxial tension test could be the most direct test to determine the tensile fracture properties of concrete, and especially at early age concrete strengths. Further work to compare mix proportions, effects of curing age against tensile strength gain. Size effect is another consideration not assessed during this test.

6 Acknowledgements

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